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Control System interaction in the VSC-HVDC Grid Connected Offshore Wind Power Plant

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SUMMARY

Conventional offshore wind power plants (OWPPs) are due to the combination of the extensive submarine cabling and possible low available short-circuit power at the point of common connection (PCC) susceptible to the harmonic instability phenomena. The instability is caused by the resonances in the electrical system which is generally located within the wind turbine generator (WTG) controller bandwidth. Some of the negative impact of the existence of harmonic instability include (but not limited to) accelerated component ageing due to increased thermal stresses and loss of power production before the source of the instability has been identified and mitigation methods have been designed and implemented. This procedure is not straightforward and can have a long lead time. The harmonic instability can have severe economic consequences for the OWPP owner due to the large investment. Harmonic stability or converter interaction studies have therefore become an important part of the system design studies of a high voltage alternating current (HVAC) grid connected OWPP. The voltage sourced converter high voltage direct current (VSC-HVDC) has become a preferred choice for grid connection of remotely located OWPPs.

As for the HVAC grid connected OWPPs, there is a need to conduct harmonic stability studies in the design phase of an HVDC grid connected OWPP. As the offshore electrical environment is significantly altered compared to the offshore network in an HVAC connected OWPP, there is a need to define the procedure of the stability study and its application for the HVDC grid connected OWPPs. The purpose of this paper is to investigate the harmonic instability phenomena in HVDC grid connected OWPPs using both frequency and time domain simulations. A good correlation at lower frequencies between the two domains is observed. However, the frequency domain is insufficient at higher frequencies (i.e. in the vicinity of the switching frequency). A combination of the two techniques is thus recommended in the OWPP design phase. Successful application of active filtering to suppress possible instabilities is illustrated.

KEYWORDS

Electromagnetic transient (EMT), Harmonics, harmonic stability, offshore wind power plant (OWPP), voltage-source converter (VSC), high voltage direct current (HVDC).

1 Introduction

WTGs with full-scale back-to-back converters are typically used in large OWPPs, which significantly increases the complexity of the OWPP structure [1]. The conventional HVAC grid connected OWPPs can be characterised as converter rich grids, with a widespread medium-voltage subsea cable network and long high-voltage cables to the transmission system [2]. The VSC-HVDC has become a preferred choice for grid connection of remotely located OWPPs [3]. This new system configuration significantly alters the offshore electrical environment compared to the offshore network in an HVAC grid connected OWPP [4]. High grid impedance is commonly considered to be the main factor in the destabilisation of the converter [5,6,7]. However, due to the OWPP characteristics, the extensive submarine cabling will inevitably create resonance(s) within the WTG converter's controller bandwidth [1,7,8]. The interaction may result in an unacceptable high harmonic distortion level [9], which will reduce the efficiency of the generation and transmission of the electrical energy in the OWPP. Furthermore, the increased harmonic distortion level will increase the thermal stresses of the power electronic devices (PEDs) and passive components such as the WTG transformer and the interturbine cables in the internal OWPP collecting grid, causing accelerated component ageing and may cause malfunctioning of the OWPP protection system. In addition, the harmonic instability may lead to excessive overvoltages, which will cause disconnection of the WTG(s), leading to loss of production, which, due to the size of nowadays OWPPs, will have a serious impact of the revenue for the owner.

Currently, the harmonic stability studies for HVAC connected OWPPs are mainly done in the frequency domain [1,7,8], since the electrical system can be analytically described and conventional indices such as e.g. the Nyquist stability criterion can be applied [1]. As outlined in [9], there are limitations to frequency domain analysis, as linearization is done on both the non-linear switching devices as well as the control system. Furthermore, saturation effects of e.g. transformers and the integrator part of the PED proportional-integral (PI) controller are neglected. These effects can (depending on the modelling detail) be included in the time domain model description. Limitations of the time domain approach include both time-consuming model implementation and initialisation of the developed model. Furthermore, the time domain approach does not directly indicate the stability margins of the system. Based on frequency and time domain harmonic stability studies in [1] and [9], respectively, it was shown that the harmonic impedance in the HVAC connected OWPP is highly affected by the number of WTGs in service. It is therefore necessary to perform in the range of thousands of study cases to cover all possible operating points of the OWPP and the external network. Similarly, a very high number of cases need to be covered in the harmonic stability studies of an HVDC grid connected OWPP. This is somewhat straightforward in the frequency domain, whereas it will be more challenging in the time domain, due to the limitations mentioned in the above and more detailed in [9].

The application of the frequency domain in the stability analysis rises the conceptual challenge of recognising the source and the load (i.e. the plant), as either the grid (in HVAC grid connected OWPPs) or the WTG converters can be treated as the source in the analysis, yielding different results [5]. The challenges become even more relevant in case of HVDC grid connected OWPPs. In this case both the load and the source are actively controlled power system devices. The time domain approach on the other hand provides a holistic approach, without the need to assign the source in the analysis.

Typically, the stability of grid connected converters are tested using an average converter model in the time domain, which is considered valid up to a frequency significantly lower than the switching frequency [10]. The application of an average converter model in the time domain is essentially the dual to the frequency domain representation (with the exception of e.g. saturation effect of transformers and the PI controller's integrator), and thus do not provide more information on the current controller's susceptibility, which is not readily available from the frequency domain model. Detailed time domain models taken into consideration the switching devices of both the WTGs and the HVDC system is considered in this work in order to provide a more realistic evaluation of the frequency domain and its application in the design phase of HVDC grid connected OWPPs. Generic models of the WTGs and the HVDC system has been developed in [11] and evaluated based on test measurements [12]. The purpose of this paper is to investigate the harmonic instability phenomena in HVDC grid connected OWPPs using both frequency and time domain simulations.

2 Model Description

Figure 1 shows a visualisation of the HVDC grid connected OWPP. The highly simplified single line diagrams in the figure also indicate possible resonance paths, as seen from the PED terminals (red for the individual/grouped WTG(s) and blue for the VSC-HVDC).

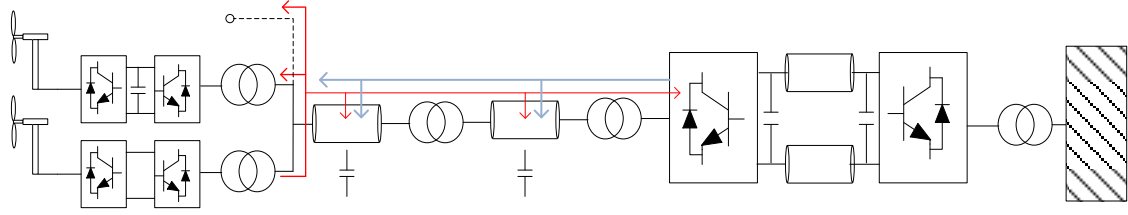


Figure 1 Simplified single-line diagram of the HVDC grid connected OWPP.

2.1 WTG Modelling

The considered WTG is a 5 MW sized type 4 WTG equipped with a permanent magnet synchronous generator (PMSG) and a two-level generator and grid side converters, shown in Figure 2. A chopper controlled resistor is used to dissipate the excess power during abnormal grid conditions. The generic model of the type 4 WTG shown in Figure 2 [13] and its associated control system is divided into a grid and a generator side, described in detail in [11].

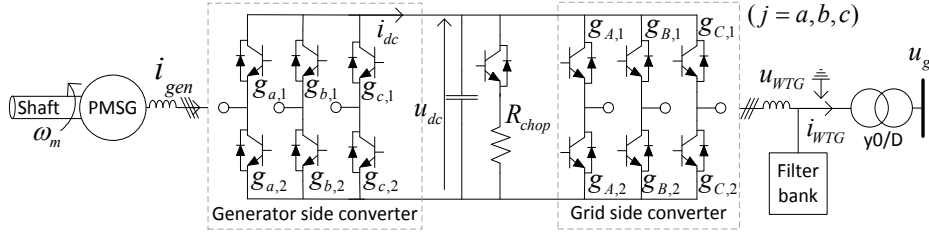


Figure 2 Simplified diagram of the type 4 WTG.

2.1 VSC-HVDC System Modelling

The HVDC system is inspired by a 7 MVA back-to-back controllable grid interface (CGI) [12] and scaled up to the ratings of the 500 MW HVDC system with a DC link voltage of $u_{dc}/2 = \pm 320$ kV. The CGI is chosen to represent the HVDC system as a model has previously been developed and evaluated based on test measurement. The CGI model verification is presented in [11], where also a more detailed description of the CGI and its modelling aspects can be found. Figure 3a shows the simplified single line diagram of the j^{th} ($j = a, b, c$) phase of the CGI. The test side of the CGI is composed of four neutral point clamped inverter (NPC) units (see Figure 3b), connected in parallel on the DC side and one NPC unit on the grid side of the converter.

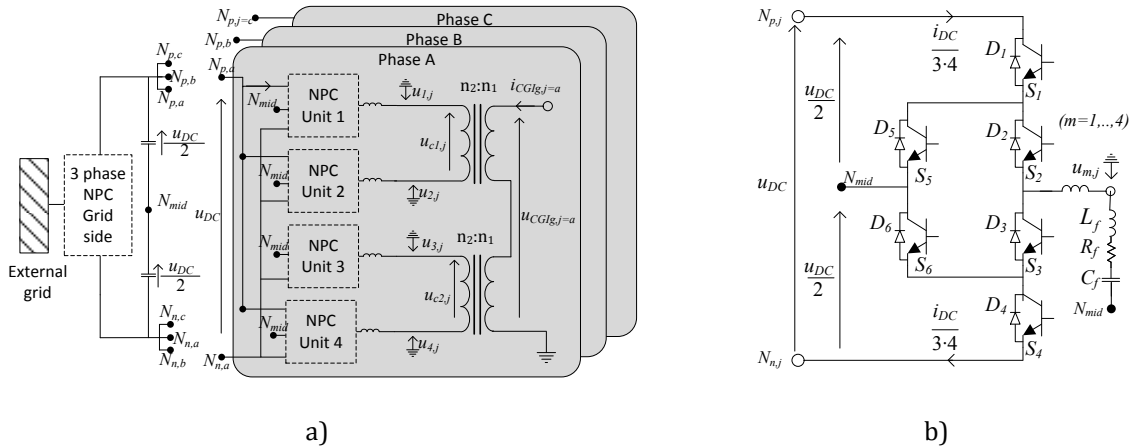


Figure 3 a) Simplified single line diagram of the CGI. m^{th} ($m = 1,2,3,4$) NPC unit.

2.1 Applied Control System in the WTGs and the HVDC System

A dual inner loop current controller operating in the rotating reference frame (RRF or dq) [14,15,16] is considered here for both the HVDC converter and the WTG, as this control methodology is typically used in commercial HVDC and WTGs, see e.g. [7] and [17].

Notch or Band rejection filters (BRFs) have been included in the control loop according to the recommendation in [7] to improve the relative harmonic stability of the system. The transfer function of the BRF is given in canonical form in (1) [8].

$$G_{BRF}(s) = \frac{s^2 + \frac{\omega_n}{Q_n}s + \omega_n^2}{s^2 + \frac{\omega_n}{Q_d}s + \omega_n^2} \quad (1)$$

where ω_n is the tuned angular frequency of the notch filter.

2.2 OWPP Representation

The OWPP is normally aggregated in the stability studies [9,11]. A description of the aggregation procedure is given in [8].

3 Harmonic Stability Evaluation

The stability issues in power systems employing PEDs is mainly attributed to [18,19]: a) The violation of the admittance ratio or Nyquist stability criterion, studied in e.g. [20-26]. A more thorough review is given in [27]. For PEDs with equivalent load and source impedances ($Z_{load}(s)$ and $Z_{source}(s)$, respectively), the system is guaranteed to be stable if the ratio $Z_{load}(s)/Z_{source}(s)$ does not encircle the point $(-1;0)$ on the Nyquist contour plot [5]. This well-established technique to investigate the system stability is referred to as the impedance-based stability criterion developed in [28]. b) The real part of input/output impedance of a VSC might appear as negative resistance in the low frequency range due to the controllers parameters, reducing the system's damping [18,19,29].

The Nyquist stability criterion is used in the analysis in this work.

3.1 Stability Indices

The Nyquist contour shows the number of encirclements and thus the stability of the closed-loop system [1,7,8]. The commonly applied gain and phase margins (GM and PM, respectively) provide a two-point measure on how close the Nyquist contour is to encircle the $(-1;0)$ point. The GM is the factor that the amplitude of the open-loop transfer function ($G_{ol}(s)$) can be increased before the system becomes unstable. The GM is the inverse of $G_{ol}(s)$, when the phase of $G_{ol}(s)$ is 180° . The PM is a measure of how much additional phase lag or time delay the system can tolerate [30].

The GM and PM are useful in the evaluation of the relative stability of the system but can be misleading as in the design of realistic control systems [8]. Alternatively, the vector gain margin (VGM) can be used [31]. The VGM is based on a sensitivity function and is defined as the shortest distance of the Nyquist contour of $G_{ol}(s)$ and the point $(-1;0)$. For the stability evaluation in OWPPs, the VGM has previously found to provide a more realistic insight on the system's relative stability [1,8].

4 Harmonic Stability Study

As previously mentioned, the number of WTGs in service (n_{WTG}) is known to be the main contributor to possible harmonic unstable operating conditions in OWPPs [1,9], and is thus taken into consideration in the stability assessment in this paper. As mentioned in the introduction, the frequency domain approach requires the selection of the source in the evaluation (i.e. either the WTGs or the HVDC). The time domain, on the other hand, provides the complete solution of the overall system stability. Here the aggregated WTGs are taken as the source in the evaluation. The procedure is essentially identical when considering the HVDC as the source in the evaluation and is omitted due to space considerations.

4.1 Frequency Domain Evaluation

Figure 4a shows the frequency response of the admittance seen from the aggregated WTG's terminals, where n_{WTG} is varied in increment of one per iteration from 1 to 100 WTGs in service. The figure provides useful information of the system characteristics. Three resonance spikes are present, located in the lower frequency range (a few hundred Hertz), mid and higher range of the frequencies considered (i.e. from 51 Hz to 2 kHz). Each of these spikes varies both in amplitude and the frequency at which they appear, depending on n_{WTG} . It should be noted that the obtained frequency characteristics in Figure 4a are calculated under the assumption that the system is symmetrical (e.g. the involved transformers, cables etc. each present equal phase impedance). In real life, inaccurate cable parameters for example, are unavoidable due to e.g. fabrication errors [11], which will also cause the phase impedances to become asymmetric. Additionally, the admittance seen from the individual WTG is different from that seen from the aggregated WTG due to the asymmetric cable collection grid's layout in an actual OWPP. The simplifications caused by the aggregation procedure described in [11] should be evaluated based on comparison with a full representation of the OWPP during the design phase of an OWPP. In [8] it was observed that the influence of the aggregated cable collecting grid on the frequency response of the OWPP is less pronounced for large OWPPs compared to smaller OWPPs. The aggregation of the OWPP might therefore have increased credibility in the harmonic stability analysis for very large OWPPs (e.g. for 0.8 GW and above). This should be evaluated during the OWPP design phase.

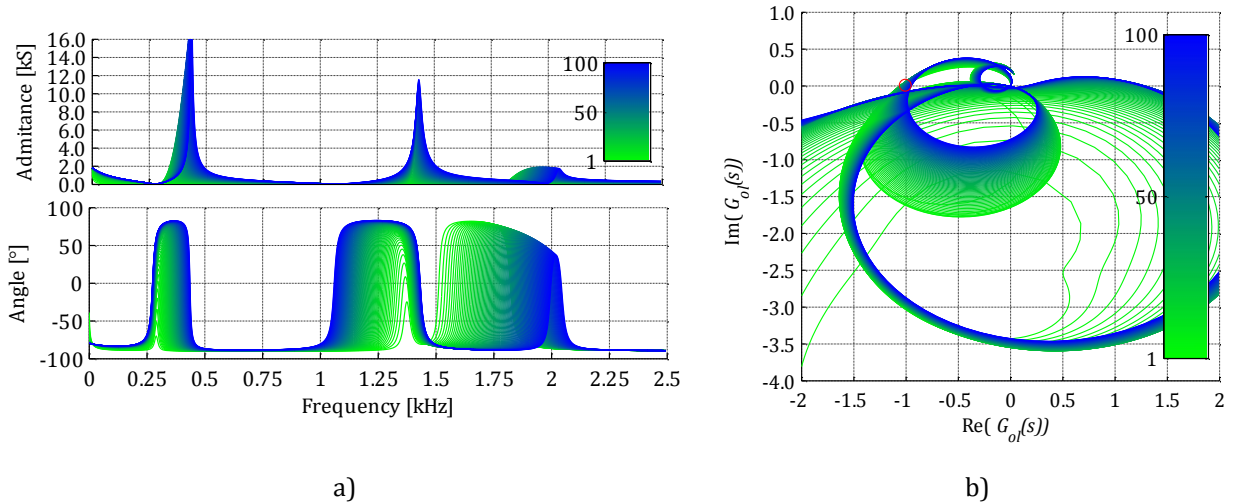


Figure 4 a) Admittance seen from WTG terminal for varying n_{WTG} from 1 (light green) to 100 WTGs (dark blue). b) Open loop Nyquist contour seen from the aggregated WTG's terminals.

Figure 4b shows the calculated open loop Nyquist contour. As can be observed, the contour is significantly affected by n_{WTG} . The system is unstable when the GM is less than unity, which is the case for $n_{WTG} \leq 50$ WTGs.

The case with $n_{WTG} = 50$ WTGs in service is considered as the system becomes unstable at this operating scenario. The calculated critical frequency in this case is 833 Hz, when the GM becomes less than unity. A BRF included in the inner current controller is used to improve the WTG's robustness toward this unstable operating condition as shown in Figure 5a.

Figure 5b shows the calculated Nyquist contours with and without the stability BRF included (blue and green curves, respectively). Introducing the BRF significantly improves the stability. A GM of 1.4 is observed for $n_{WTG} = 50$ WTGs, which is considered appropriate.

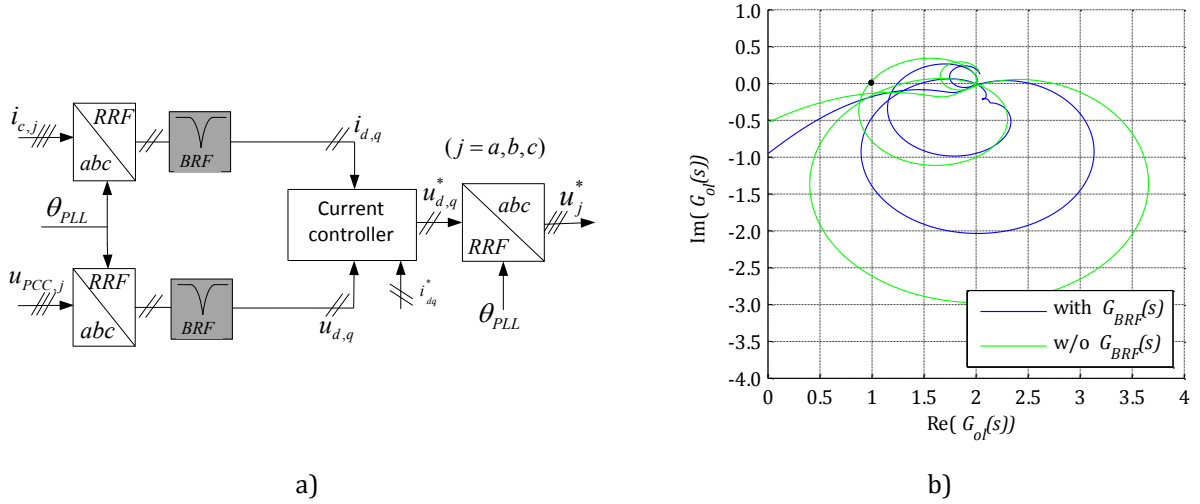


Figure 5 a) Positive sequence inner current controller equipped with the BRF for attenuating possible interaction with the electric system external to the PED. The negative sequence controller is not shown in the figure, but has a similar structure. b) Open loop Nyquist plot with and without the BRF in the direct chain of the current controller.

4.2 Time Domain Evaluation

In order to correlate the above frequency domain results to the time domain model, Figure 6 shows the simulated currents at the 34 kV side of the WTG transformer for $n_{WTG}=50$ WTGs. As predicted by the Nyquist plot in Figure 4b, the time domain model is unstable for this operating scenario. The unstable system's variables would increase toward infinity if there were no limiting factors present such as e.g. the DC-link voltage of the PEDs.

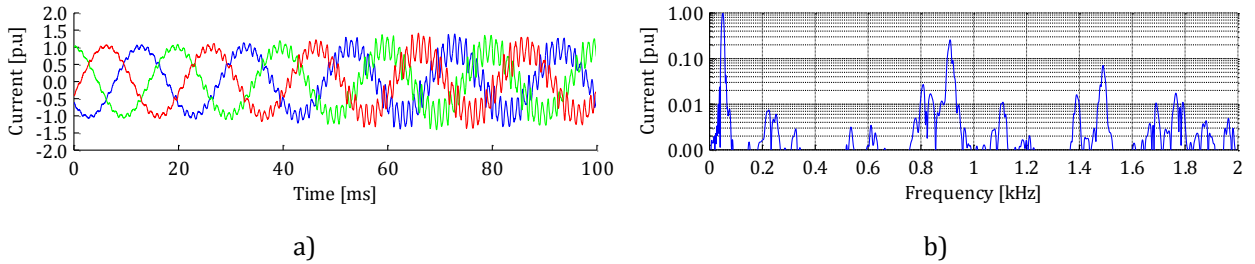


Figure 6 a) Time domain waveforms at the 34 kV side of the WTG transformer for $n_{WTG}=50$ WTGs. b) FFT plot of the phase A current in figure a.

In the preceding frequency domain evaluation it was possible to stabilise the system by the introduction of the stability BRF in Figure 5b. However, the inclusion of the BRF in the time domain model do not yield a stable system as can be seen in Figure 7a, where a 0.5 p.u frequency component located at 1882 Hz is superimposed on the current waveforms. This frequency correlates well with the highest resonance in the admittance plot in Figure 4a. However, the value of the open loop transfer function G_{ol} at 1882 Hz is $0.13 \angle -230^\circ$ obtained from the frequency domain model, which is far from the unstable region (i.e. neither the minimum GM, PM or VGM are violated). There are therefore some limitations to the frequency domain, as it only considered valid in the frequency range well below the switching frequency [10]. Care should therefore be exercised when using the frequency domain in the stability evaluation.

The further inclusion of a BRF tuned 1882 Hz is considered and the simulated currents are reported in Figure 7b. The application of the two BRFs in the current control system successfully suppresses the new instability observed in the time domain in Figure 7a. The frequency components present in Figure 7a are practically eliminated in Figure 7b demonstrating the successful application of active filtering.

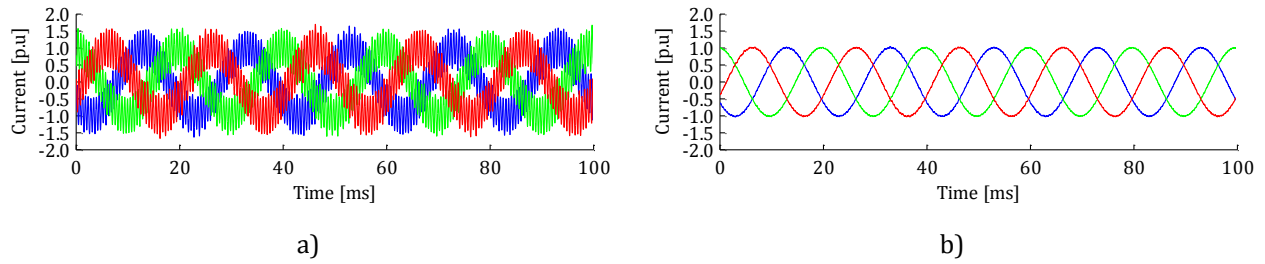


Figure 7 Time domain waveforms at the 34 kV side of the WTG transformer for $n_{WTG}=50$ WTGs. a) Inclusion of a BRF tuned at 833 Hz from the frequency domain analysis. b) Additional BRF tuned at 1882 Hz in order to suppress the instability in figure a.

5 Conclusion

This paper has addressed the harmonic stability in HVDC grid connected OWPPs, which is considered a core concern in the industry. The focus has been on the evaluation of conventional and linearized frequency domain analysis methods such as the Nyquist stability criterion. The evaluation has been conducted using time domain simulations in PSCAD/EMTDC with detailed converter model representations, including the switching devices of the WTGs and the HVDC converter station.

The paper has demonstrated good correlation between the time and frequency domain methods for the stability analysis. However, limitations of the frequency domain were observed when resonances at higher frequencies exist (i.e. in the vicinity of the switching frequency and above the bandwidth of the current controller). Therefore, it is proposed to conduct the analysis primarily in the frequency domain. Once all the considered operating scenarios are covered (typically in the excess of 1000) a few cases should be selected and repeated in the time domain, which is both more challenging and more time consuming than the frequency domain method.

It was shown that an application of active filtering in WTGs by means of additional BRF (i.e. notch filter) in the main control chain can potentially reduce harmonic emission at the point of interest (e.g. PCC) and improve overall stability in OWPPs. This can be achieved by reducing the harmonic content generated by converters as well as changing existing resonances (i.e. improving damping or shifting resonance frequencies). Improving the converter's controller rejection capability called active damping is a certain type of active filtering. The converter may be controlled adaptively or tuned to suppress selected harmonic components. Thus there is no need to interfere with the WPP design.

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